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A CALORIMETRIC DETERMINATION OF THERMAL EMISSIVITY

A THESIS

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SUMMARY

The object of this investigation was to assemble an apparatus for experimentally determining the thermal emissivity of a polished metal surface.

After reviewing the literature for possible test methods a calorimetric technique was selected which basically consisted of measuring the electrical power required to maintain an internally heated sample at a steady state temperature while suspended in an evacuated chamber.

The sample was a hollow copper cylinder with spherical ends and its outer surface was nickel plated and polished. Power was furnished by a resistance heater within the sample and a thermocouple monitored the surface temperature.

By analysis it was shown that substantial amounts of energy were transferred from the sample by gaseous and lead wire conduction. Upon correcting for these losses the total hemispherical emissivity for the polished nickel surface was found to range from 0.054 at a temperature of 259° F to a value of 0.069 at 463° F. These measured emissivity values were within the range of published data for polished nickel and an increase in the emissivity value with increasing temperatures was observed which is characteristic of polished metal surfaces.

The estimated maximum error in the emissivity was shown to be ± 26 per cent at 259° F and was primarily caused by the uncertainty of the gaseous conduction correction. As the sample temperature was increased the conduction losses became less significant and the estimated error

in the emissivity at 463° F was ± 17 per cent. An analysis showed that the accuracy would be greatly improved if the heat transferred by gaseous conduction were reduced to a negligible amount by utilizing a vacuum system capable of maintaining pressures several magnitudes lower than the pressure of 10^{-3} mm Hg obtained in this investigation.

Heat loss from the sample by lead wire conduction was a source of error which proved to be difficult to minimize. The need for a more precise method of determining these lead wire losses was emphasized by an analytical approximation.

CHAPTER I

INTRODUCTION

There is no theory at present for the precise calculation of thermal emissivity and quite often no published data can be found for the surface in question. Wide variations in the published emissivity values are also encountered and are generally caused by differences in the surface condition of the material.

Recent experimental studies on heat exchange by natural convection pointed out that the correction for thermal radiation losses could not be accurately made because a precise emissivity value was not available. The expressed need for the capability of experimentally measuring the total hemispherical emissivity prompted this investigation. A polished nickel plated surface was chosen in an effort to provide data for a natural convection study in progress at that time. Interest was also stimulated by current satellite and space vehicle activity which places increased importance on the thermal radiation property.

A literature search revealed that thermal emissivity is generally determined by either reflectance techniques or calorimetric techniques. Spectral variations of emittance are more suitably measured by the reflectance approach and the values obtained are for normal emittance which must then be converted to hemispherical emittance. According to Dunkle (1), this method involves complex equipment and instrumentation and many sources of error are incurred.

Two methods are generally considered in the calorimetric technique. Both methods involve suspending a sample in an evacuated enclosure which is at a lower temperature than the sample temperature. The emissivity can then be determined either by measuring the power required to maintain the internally heated sample at a constant temperature or by measuring the temperature decay versus time as the preheated sample cools to the temperature of the enclosure. Helpful descriptions of the constant temperature method were found in papers by Shaw (2) and Drummeter and Goldstein (3). The temperature decay method was interestingly outlined in a paper by Butler and Inn (4). For this investigation the constant temperature method was chosen because the required equipment was more readily available and the sources of error appeared to be fewer. A comprehensive discussion on the relative merits of thermal radiation measuring techniques was later found in a paper by Gaumer et al. (5) which strongly supported the constant temperature method for total hemispherical emissivity measurements.

CHAPTER II

INSTRUMENTATION AND EQUIPMENT

After several design concepts were considered, it was decided to assemble a simple apparatus using readily available equipment and materials. The experience gained could then be applied to a more sophisticated apparatus with greater assurance of satisfactory performance.

Test Sample

The sample was fabricated from copper round stock and machined to a diameter of one inch with spherical ends and an overall length of six inches. A 3/8 inch diameter axial hole was drilled to a depth of 5 11/16 inches for the electric heater. Provision was made for the installation of three thermocouples by drilling three radial holes, size 40, through one wall of the sample. The holes were equally spaced radially and axially. A cylindrical plug, 3/8 inch long, with a 1/8 inch axial hole was machined to slip fit into the open end of the sample. To facilitate a mechanical stop for the plug and an attach point for a suspension wire, a number 50 radial hole was drilled through the sample approximately 3/8 inch from the open end, into which a short length of stainless steel wire was inserted. The sample was completed when it was nickel plated and polished by the Simmons Plating Company, Atlanta, Georgia. A surface roughness of 10 RMS was measured with a surface indicator made by Brush Electronics Company, Model Number BL-110.

Resistance Heater

The electrical resistance heater was constructed by lathe winding approximately 18 feet of nichrome alloy wire, size 34, 17 ohms per foot, on to a 1/8 inch diameter glass tube five inches long. Both ends of the nichrome wire were twisted and soldered to copper lead wires and one of the lead wires was then routed through the inner diameter of the glass tube. After closing one end of a 1/4 inch diameter glass tube by flame heating to resemble a test tube, the heater element was inserted and the open end was cemented closed with furnace cement. The lead wire was 30 gauge copper wire with one mil of teflon insulation and extended from the heater to the chamber wall receptacle.

Vacuum Chamber

A sectional illustration of the vacuum chamber is shown in Figure 1, page 5. Flanges made of 1/4 inch copper plate were silver soldered to a 7 1/4 inch length of two inch I.P.S. seamless copper pipe having a wall thickness of 0.156 inches. The ends of the chamber were closed by bolting 1/4 inch copper end plates to the flanges and sealing was accomplished by a size 36 rubber "O-ring". Stopcock lubricant was placed on the mating surfaces to improve the vacuum seal.

Provision was made to route the wires to the sample by drilling a 1/8 inch diameter hole in the center of the top end plate. Chamber evacuation was facilitated by drilling four 1/4 inch diameter holes equally spaced on a 1 1/2 inch diameter through the top cover plate. An outer chamber was formed by silver soldering a copper reducing coupling to the outer surface of the top cover plate. The resulting configuration provided adequate evacuation area while preventing the sample from "seeing"

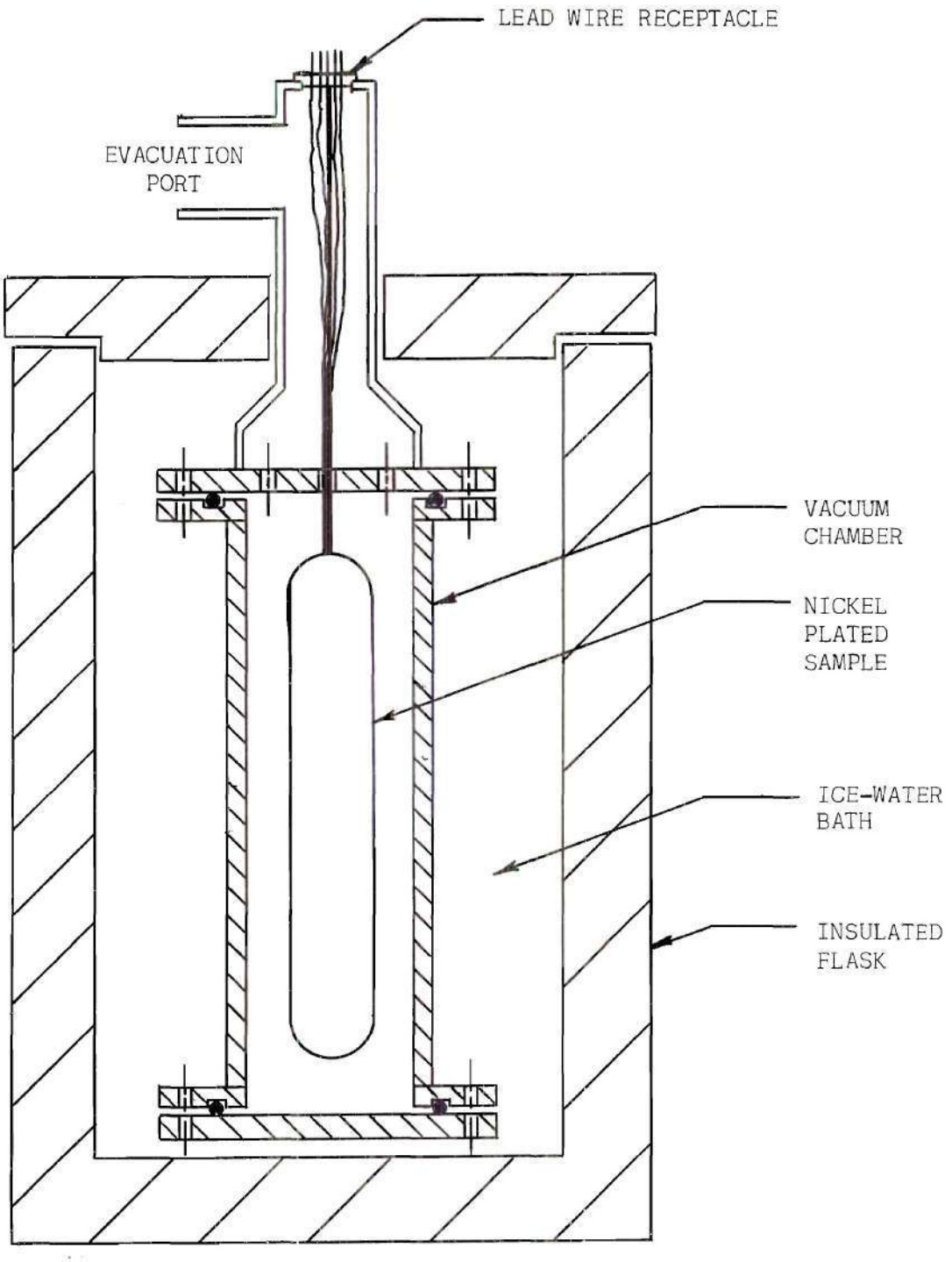

Figure 1. Sectional View of Vacuum Chamber

down the vacuum line. Standard copper tubing and fittings completed the chamber hardware.

It was desired that the chamber absorb the thermal radiation from the test sample with a minimum of reflection and a means for accomplishing this was suggested in an article by Roger E. Gaumer (6) which cited a measured total absorptivity of 0.908 for a surface treated with "Ebonol C". At the recommendation of the product manufacturer, Enthone Incorporated, New Haven, Connecticut, "Ebonol C Special" was used because better adherence was claimed.

The chamber components were cleaned with a strong detergent and water rinsed. To produce a dull surface the chamber was etched for three minutes in a solution of muriatic acid, 10 per cent by volume, and water at room temperature, followed by a cold water rinse. The blackening solution consisted of "Ebonol C Special" mixed with water in the proportion of 1 1/2 pounds of salts for each gallon of solution. A large glass beaker was used to mix the solution which was then heated to 210° F. Following a seven minute submergence in the solution, the components were thoroughly rinsed with water and dried. The surfaces treated in this manner were very black and care was exercised not to rub down the fine surface nap which consisted of thousands of black cupric oxide needles.

A more effective method of blackening the chamber was later discovered in an article by R. E. Gaumer, et al. (7). By simply spraying the surfaces with a coating of Parson's Optical Black lacquer which is distributed by The Eppley Laboratory, Inc., Newport, Rhode Island, a total emissivity of 0.97 may be obtained.

Chamber Bath

A wide mouth Virtis Fluo-war flask with an insulated cover was used to contain the ice water bath in which the vacuum chamber was submerged. Maintaining the chamber walls at ice water temperature was deemed adequate for the present investigation, however the flask was suitable for use with dry ice-solvent, liquid nitrogen, or liquid air baths as required for more accurate emissivity measurement or for emissivity measurement at lower temperatures.

Vacuum Equipment

The major components of the vacuum system were a two-stage series-connected vacuum pump, CENCO model number 91505, and a double range McLeod gauge, CENCO model number 94151. Heavy wall rubber tubing for high vacuum was used to connect the pump to the gauge and chamber along with a glass bleeder valve and miscellaneous hose clamps and copper tube fittings. A glass stopcock was used to seal off the McLeod gauge when the system was not in use. Stopcock lubricant for high vacuum was used on all hose connections and a liberal coating of Glyptal paint was applied to the two threaded connections along with an external application of Apiezon sealing compound.

Temperature Measuring Instrumentation

Sauereisen No. 63 electric heater cement was used to retain the 28 gauge chromel-alumel thermocouples in the radial holes of the sample. Temperature measurement error was minimized by routing the fiberglass insulated thermocouple wire through the interior of the sample and by insulating the junctions at the chamber wall receptacle and selector

switch. The thermocouple potential was measured with a Leeds and Northrup potentiometer utilizing an ice point reference junction as shown in Figure 2 on page 9.

The accuracy of the three thermocouples mounted in the sample was checked by measuring the temperature of boiling water and comparing the readings with the actual water temperature obtained from the steam tables. All thermocouple readings were within a half of one degree of the correct temperature. Chamber wall temperature was not monitored directly, but the temperature of the surrounding ice water bath was periodically measured.

Power Equipment

Electrical power to the sample heater was controlled with a Superior Electric Company variable transformer and was measured with a Weston wattmeter, model number 310, as shown in Figure 3 on page 10. The power to the sample was measured on the low end of the wattmeter range and was accurate within ± 0.04 watts.

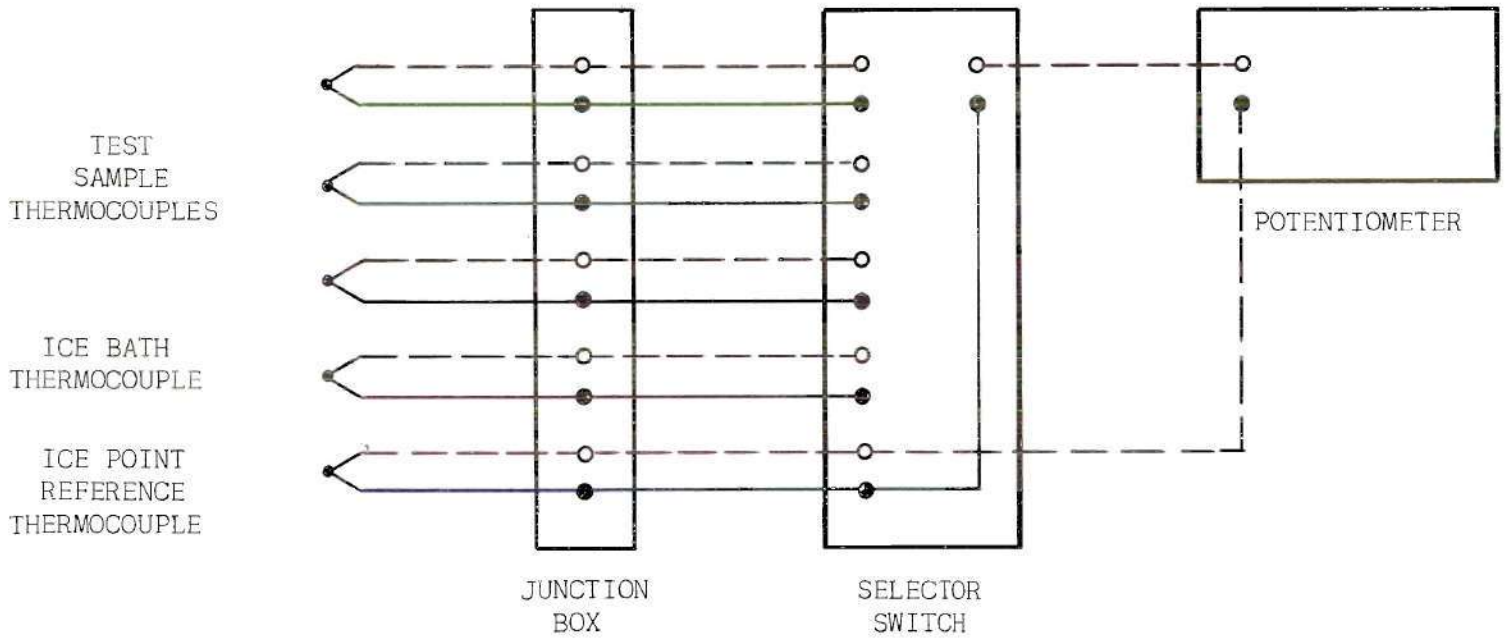

Figure 2. Schematic of Thermocouple Circuit

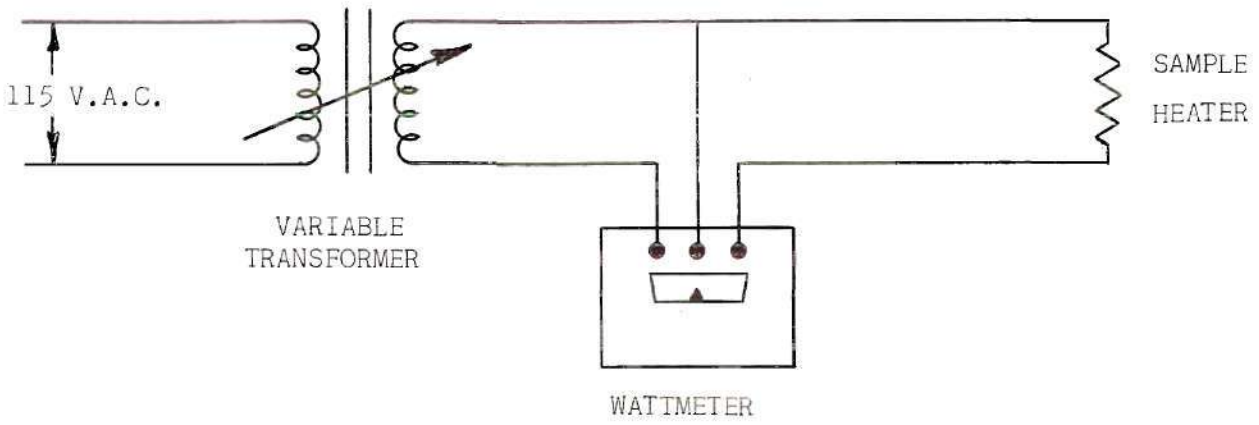

Figure 3. Schematic of Power Circuit

CHAPTER III

PROCEDURE

The sample was thoroughly cleaned with trichlorethylene to remove any oil films prior to installation in the chamber. In order to remove the condensable vapors from the vacuum system it was necessary to operate the vacuum pump with the gas ballast valve open for at least 24 hours. The gas ballast valve allows regulation of atmospheric air flow into the compression cycle of the exhaust stage and by reducing the compression ratio of the present vapor volume in the stage, the vapors are prevented from condensing into the pump oil. Entrapped water vapor is the primary condensible vapor usually encountered according to M. Pirani and J. Yarwood (8). Following the initial degassing period, the gas ballast valve was gradually closed over a twelve hour period. The best vacuum which could be obtained was 1×10^{-3} mm Hg (1 micron) although the pump specification claims an ultimate vacuum capability of 0.1 micron when connected directly to a trapped-McLeod gauge. All data were taken with vacuum conditions ranging between 1.0 and 1.5 microns.

A data point was obtained by setting the variable transformer at a power setting and submerging the chamber in an ice water bath until the sample temperature reached equilibrium. By closely monitoring the sample temperature on several data runs it was determined that a measurable change in the sample temperature did not occur after a twelve hour period. A minimum of twelve hours was therefore allowed for temperature stabilization at each data point. The sample surface temperature was

then recorded along with the chamber pressure, uncorrected input power, and power loss in the wattmeter.

When it was observed that the three sample thermocouples were consistantly reading within a spread of one °F, two of the thermocouples were removed to reduce conduction losses. The size of the power leads was also reduced from 24 gauge to 30 gauge copper wire in an effort to reduce conduction losses.

A total of over forty data points were obtained during the investigation. The majority of these data were voided when changes were made to the test equipment which improved the accuracy. The data points obtained for temperatures below 250° F were quite scattered and were discarded as a result of the low power levels which could not be accurately set or measured with the available equipment. Thus a total of nine usable data points were obtained, four while decreasing the temperature, three while increasing the temperature, and two points while again decreasing the temperature to verify repeatability.

CHAPTER IV

DISCUSSION OF RESULTS

Figure 4 on page 14 presents the experimental results of this thesis by graphically showing the measured value of the total hemispherical emissivity of the nickel plated sample over a temperature range of approximately two hundred degrees farenheidt. When compared with published data, a general agreement can be seen both in the emissivity values and in the emissivity increase with increased temperature which is a characteristic property of polished metal surfaces.

These results were obtained by using the equation presented by Eckert (9) for heat exchange by radiation for concentric spheres or cylinders.

$$Q_R = \frac{\sigma A_s}{(\frac{1}{\varepsilon_s}) + (\frac{A_s}{A_c})(\frac{1}{\varepsilon_c} - 1)} (T_s^4 - T_c^4) \quad .$$

In this experiment the emissivity of the inner cylinder is small relative to the emissivity of the surrounding chamber and the second term in the denominator can be neglected with an error of less than 0.2 per cent. Thus the equation for the total emissivity was expressed as

$$\varepsilon_s = \frac{Q_R}{A_s \sigma (T_s^4 - T_c^4)}$$

However, the energy supplied (Q_s) to the sample is not only exchanged by radiation (Q_R) but substantial amounts are exchanged by gaseous conduction

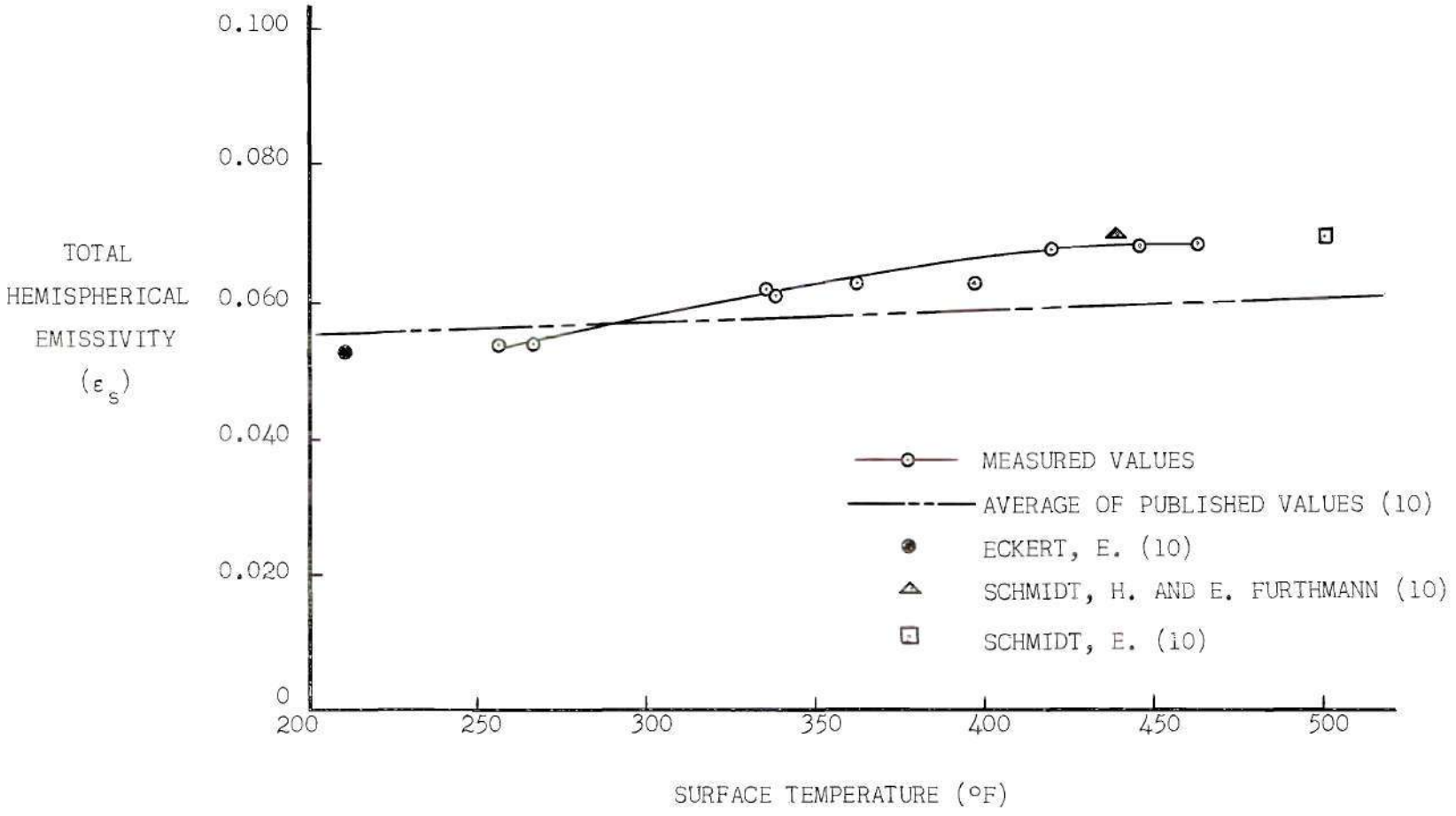

Figure 4. Comparison of the Measured Values of Total Hemispherical Emissivity With Published Values for Polished Nickel

(Q_c) and lead wire conduction (Q_L). The equation therefore becomes

$$\varepsilon_s = \frac{Q_s - Q_c - Q_L}{A_s \sigma (T_s^4 - T_c^4)}$$

The magnitude of Q_c and Q_L were calculated to be as much as 33 per cent and 8 per cent respectively of the total energy Q_s supplied at the lowest sample temperature. Corrections for I^2R losses in the power leads were not made since the losses were less than 0.1 per cent of Q_s.

A maximum error in ε_s of ± 26 per cent was estimated as shown in Appendix C and occurred at the low end of the temperature range. This high uncertainty was introduced predominantly by the magnitude of the Q_c term. Gaseous conduction calculations in Appendix A show that the molecular mean free path of the gas in the chamber is greater than the chamber dimension and heat exchange is by molecular conduction which is directly proportional to the pressure. The estimated maximum error in the Q_c term was ± 25 per cent because the composition of the gas was not precisely known and was assumed to be a mixture of air and water vapor. By utilizing evacuation equipment capable of obtaining pressures as low as 10^{-5} mm Hg, the accuracy would greatly improve since the gaseous conduction would then be less than 0.5 per cent of Q_s.

CHAPTER V

CONCLUSIONS

The total hemispherical emissivity of a sample surface can be experimentally determined by a relatively simple calorimetric technique. The accuracy of the results was found to be predominently controlled by the degree to which the non radiant energy losses could be minimized.

Heat conduction by the residual gas in the evacuated chamber was the largest error inducing energy loss encountered and it was found to be directly proportional to the chamber pressure. This source of error may be readily reduced to a negligible level by suitable evacuation equipment.

Energy losses by conduction through the lead wires was difficult to accurately calculate and appears to be the most difficult source of error to minimize. The size of the lead wires must be kept as small as possible.

The measured values of total hemispherical emissivity of polished nickel were in good agreement with published values and were observed to increase with increasing temperature as is characteristic for polished metals.

CHAPTER VI

RECOMMENDATIONS

It is recommended that the following improvements be made to the apparatus described herein for any future calorimetric emissivity measurements:

1. Replace the vacuum pump and rubber hose connections with an evacuation system capable of maintaining a chamber pressure of at least 10^{-5} mm Hg.

2. Reduce the ratio of the sample mass to sample area. This will allow smaller suspension wire to be used and will also greatly reduce the time required for the sample temperature to reach equilibrium.

3. The chamber walls may be blackened more easily and effectively by spray coating with Parson's Optical Black Lacquer in lieu of a chemical surface treatment.

4. Improve the accuracy of the input power measurement by using a more accurate wattmeter or by other means.

A brief literature search failed to reveal an accurate method for calculating the heat conducted from an isothermal heat source to an isothermal heat sink by a connecting wire in a partially evacuated atmosphere. An exact solution to this problem would be highly useful in making lead wire conduction loss corrections.

APPENDIX A

ANALYSIS OF THE ENERGY EXCHANGED BY GASEOUS CONDUCTION

In addition to the heat transferred from the sample by thermal radiation and lead wire conduction, heat was transferred by the gas remaining in the chamber. According to Guthrie and Wakerling (11), the mean free path of air molecules at a pressure of 1.0 micron of mercury and 60° F is about two inches which is greater than the one half inch distance between the sample and chamber wall. Thus the rate of energy transfer per unit area of the specimen is by molecular conduction and can be calculated with the following equation according to Dushman (12).

$$q_c = \alpha_n \theta p \sqrt{\frac{273.2}{T_i}} (T_s - T_i)$$

The temperature of the chamber walls, T_c, was substituted for the temperature of the incident molecules, T_i. Adjustment for the radii r_s and r_c, $(r_c > r_s)$, of the coaxial cylinders was made in the adjusted accommodation coefficient α_n where

$$\alpha_n = \frac{\alpha}{1 - (1 - \alpha)(\frac{r_s}{r_c})}$$

Although a specific value for the accommodation coefficient α could not be found for nickel, values for polished metal surfaces were noted in the literature to range from 0.85 to 0.95. A value of 0.90 ± 0.05 was therefore selected for α which results in a value of 0.95 ± 0.08 for α_n. The molecular heat conductivity term θ is given by Dushman (12) as

$$\theta = 1/2 \left(\frac{\gamma + 1}{\gamma - 1}\right) \sqrt{\frac{\bar{R}}{2\pi}} \quad \frac{1}{\sqrt{273.2M}}$$

This reduces to

$$\theta = \frac{1.468 \times 10^{-5}}{\sqrt{M}} \left(\frac{r + 1}{r - 1}\right)$$

where γ is the specific heat ratio and M is the molecular weight of the gas.

The composition of the gas in the chamber was not readily known because of the possibility of leakage from both the surrounding air and the ice water bath. It was therefore assumed that the gas was a mixture of air and water vapor having a molecular weight of 23 and a specific heat ratio of 1.36.

The rate of energy transfer for the entire surface of the sample is

$$Q_c = q_c A_s$$

and was calculated to be

$$Q_c = 1.28 \times 10^{-3} (p)(T_s - T_c)$$

The values for Q_c that are tabulated in Appendix F were determined with the preceding equation.

APPENDIX B

ANALYSIS OF THE ENERGY EXCHANGED BY LEAD WIRE CONDUCTION

An analytical approximation of the heat which was conducted by the thermocouple wire, power leads, and suspension wire was made by using a model as shown in Figure 5 on page 22. The analysis is similar to the one presented by Drake (13) for one-dimensional steady state heat conduction in a rod, except that the heat being conducted along the rod is being lost to the surroundings by gaseous conduction and thermal radiation rather than by convection. The equation describing the axial conduction is

$$\frac{d^2T}{dx^2} = \frac{Q_H}{k}$$

where Q_H is the rate of heat exchange by gaseous conduction and thermal radiation per unit volume of rod. Substituting for Q_H:

$$\frac{d^2T}{dx^2} - \frac{\varepsilon_{1-2}\sigma C \delta x}{k A \delta x}(T^4 - T_c^4) - \frac{k_g C \delta x}{k A \delta x}(T - T_c) = 0$$

To facilitate a particular solution, the equation was rearranged as

$$\frac{d^2T}{dx^2} - C_1T^4 - C_2T + C_3 = 0$$

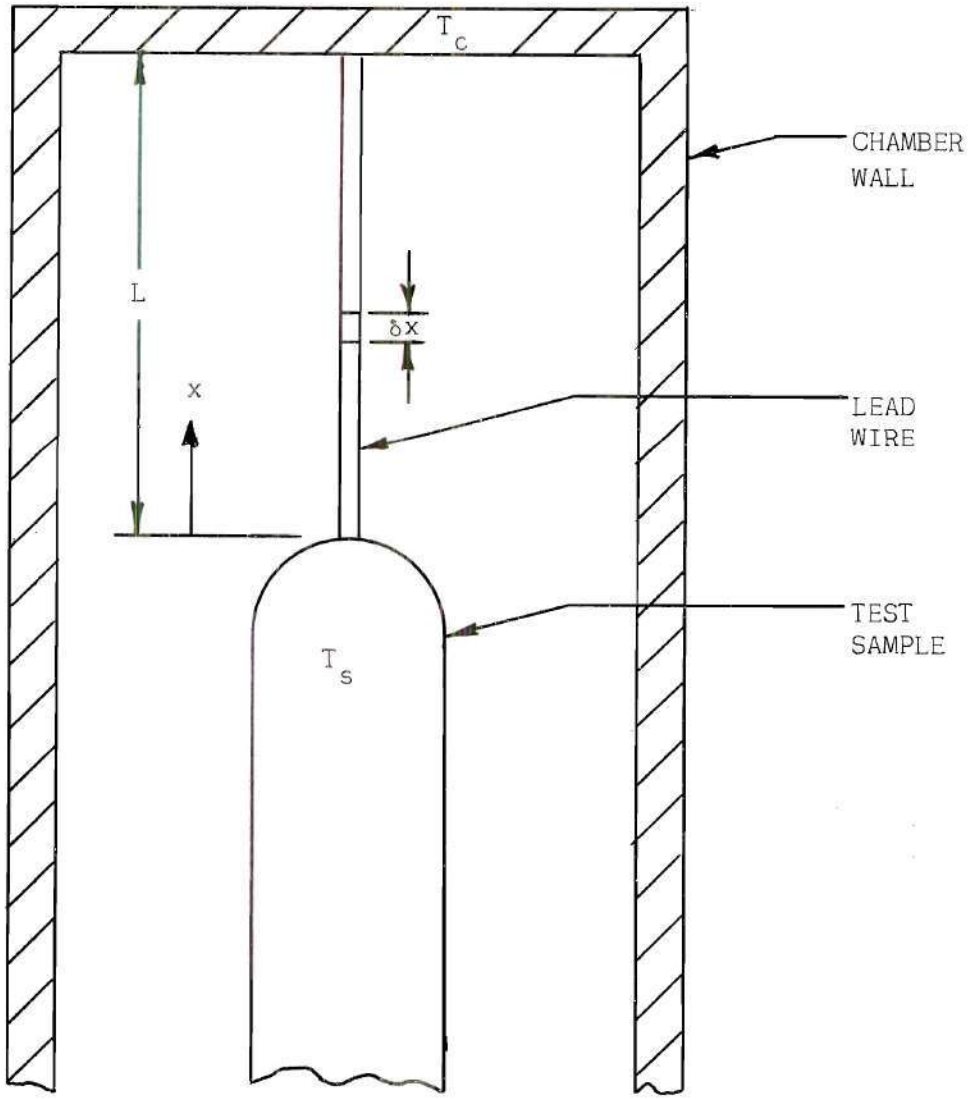

Figure 5. Lead Wire Conduction

where $$C_1 = \frac{\varepsilon_{1-2}\,\sigma\,C}{kA}$$

$$C_2 = \frac{k_g\,C}{kA}$$

$$C_3 = \frac{\varepsilon_{1-2}\,\sigma\,C}{kA}\,T_c^4 + \frac{k_g\,C}{kA}\,T_c$$

At this point a linear approximation of T^4 was made with an error of less than four per cent for the range of temperatures considered in this investigation.

$$T^4 \approx 2.165 \times 10^8 T - 1.300 \times 10^{12}$$

The resulting differential equation was

$$\frac{d^2T}{dx^2} - C_4 T + C_5 = 0$$

where $$C_4 = 2.165 \times 10^8 C_1 + C_2$$

$$C_5 = C_3 + 1.300 \times 10^{12} C_1$$

The boundary conditions are:

$$x = L, \quad T = T_c$$

$$x = 0, \quad T = T_s$$

Using routine methods and the above boundary conditions, it can be shown that

$$\left.\frac{dT}{dx}\right)_{x=0} = \left[T_c - T_s \cosh \sqrt{C_4}\, L - \frac{C_5}{C_4} + \frac{C_5}{C_4} \cosh \sqrt{C_4}\, L\right] \frac{\sqrt{C_4}}{\sinh \sqrt{C_4}\, L}$$

The temperature gradient at the sample end of the wire (x = 0) was then calculated for each lead wire and substituted in the following equation to obtain the heat flow from the sample through each lead wire.

$$Q_L = - kA \left.\frac{dT}{dx}\right)_{x=0}$$

The accuracy of the equation for Q_L is limited by the error introduced by the linear approximation of T^4. Also extensive error is encountered when the thermophysical property values are selected for the various lead wire materials. For this reason the data presented in Appendix F for Q_L are estimated to have a maximum error of ± 50 per cent. For the materials used in this investigation the total lead wire heat conduction from the sample was calculated to be

$$Q_L = 10.53 \times 10^{-4} T_s - 0.66 \quad .$$

APPENDIX C

ESTIMATED MAXIMUM ERROR

The equation for calculating the thermal emissivity is

$$\varepsilon_s = \frac{Q_R}{A_s \sigma (T_s^4 - T_c^4)}$$

If the term $(T_s^4 - T_c^4)$ is treated as one variable τ, the total derivative of this equation is

$$d\varepsilon_s = \frac{\partial \varepsilon_s}{\partial Q_R} dQ_R + \frac{\partial \varepsilon_s}{\partial A_s} dA_s + \frac{\partial \varepsilon_s}{\partial \tau} d\tau$$

$$d\varepsilon_s = \frac{1}{A_s \sigma \tau} dQ_R + (-1)\frac{Q_R}{A_s^2 \sigma \tau} dA_s + (-1)\frac{Q_R}{A_s \sigma \tau^2} d\tau$$

$$d\varepsilon_s = \varepsilon_s \left(\frac{dQ_R}{Q_R} - \frac{dA_s}{A_s} - \frac{d\tau}{\tau} \right)$$

Thus the total error is expressed as

$$\frac{d\varepsilon_s}{\varepsilon_s} = \frac{dQ_R}{Q_R} - \frac{dA_s}{A_s} - \frac{d\tau}{\tau}$$

The total error is at its maximum when the terms on the right are added and the power and temperature terms are a minimum. The estimated maximum error can be expressed as

$$\text{estimated maximum error} = \left|\frac{dQ_R}{Q_R}\right| + \left|\frac{dA_s}{A_s}\right| + \left|\frac{d\tau}{\tau}\right|$$

Since the power Q_R is calculated by subtracting Q_c and Q_L from Q_s, the error will be

$$dQ_R = \left|dQ_s\right| + \left|dQ_c\right| + \left|dQ_L\right| \quad .$$

By taking the total derivative of τ and adding the absolute value of each term, the error $d\tau$ is found to be

$$d\tau = \left|4T_s^3 dT_s\right| + \left|-4T_c^3 dT_c\right|$$

Considering the term dA_s to be negligible, the estimated maximum error may now be calculated by substituting the following values which correspond to point number 9 in Appendix F.

$$Q_s = 1.25 \pm 0.04 \text{ watts}$$

$$Q_c = 0.40 \pm 0.10 \text{ watts}$$

$$Q_L = 0.10 \pm 0.05 \text{ watts}$$

$$T_s = 719^\circ \text{ R} \pm 1^\circ \text{ R}$$

$$T_c = 492^\circ \text{ R} \pm 1^\circ \text{ R}$$

estimated maximum error =

$$\pm\left[\left|\frac{0.04+0.10+0.05}{1.25-0.40-0.10}\right| + \left|\frac{\left|4(719)^3(1)\right| + \left|-4(492)^3(1)\right|}{(719)^4 - (492)^4}\right|\right] \times 100$$

estimated maximum error = ± 26 per cent.

As the temperature of the sample is increased the conduction losses become less significant and the estimated error decreases to ± 17 per cent at 463° F.

APPENDIX D

SAMPLE CALCULATION

The equation used to calculate the total hemispherical emissivity is

$$\varepsilon_s = \frac{Q_s - Q_c - Q_L}{A_s \sigma (T_s^4 - T_c^4)}$$

The following sample calculation is given for point number 1 tabulated in Appendix F.

$Q_s = 3.70$ watts

$Q_c = 1.28 \times 10^{-3}(p)(T_s - T_c)$

$= 1.28 \times 10^{-3}(1.4)(446 - 32) = 0.74$ watts

$Q_L = 10.53 \times 10^{-4} T_s - 0.66$

$= 10.53 \times 10^{-4}(446 + 460) - 0.66$

$= 0.955 - 0.66 = 0.30$ watts

$A_s = 18.76(\text{inches})^2$

$$\varepsilon_s = \frac{(3.70 - 0.74 - 0.30)(3.406)(144)}{(18.76)(0.1714 \times 10^{-8})(906^4 - 492^4)}$$

$\varepsilon_s = 0.069$

APPENDIX E

NOMENCLATURE

A_c	Inner surface area of vacuum chamber
A_s	Surface area of sample
C	Circumference
k_g	Gaseous conduction coefficient of heat transfer
k	Thermal conductivity
L	Length of lead wire
M	Molecular weight
p	gas pressure
Q	Heat transferred
Q_c	Heat transferred from sample by gaseous conduction
Q_H	Heat transferred from leads by gaseous conduction and radiation per unit volume of lead wire
Q_L	Heat transferred from sample through leads
Q_R	Heat transferred from sample by radiation
Q_S	Total energy supplied to sample
q_c	Heat transferred from sample by gasecus conduction for a unit of surface area
$\bar{R}$	Universal gas constant
r_c	Inner radius of cylindrical vacuum chamber

r_s	Radius of cylindrical sample
T	Temperature
Tc	Temperature of chamber
T_i	Temperature of incident molecules
T_s	Temperature of sample
t	Temperature
x	Distance from sample
α	Accommodation coefficient
α_n	Accommodation coefficient adjusted for radii
ε_s	Total hemispherical emissivity of sample
ε_{1-2}	Radiative interchange factor
θ	Molecular heat conductivity
σ	Stefan-Boltzman constant
γ	Specific heat ratio
τ	Fourth power temperature difference, $(T_s^4 - T_c^4)$
μ	Microns of mercury

APPENDIX F

TABULATION OF EXPERIMENTAL DATA

POINT NUMBER	t_s MV	t_s °F	t_c °F	p μ	Q_S WATT	Q_c WATT	Q_L WATT	Q_R WATT	ε_s
1	9.33	446	32	1.4	3.70	0.74	0.30	2.66	0.069
2	9.26	398	32	1.5	2.95	0.70	0.24	2.01	0.063
3	6.98	340	32	1.3	2.10	0.51	0.18	1.41	0.061
4	5.35	267	32	1.25	1.27	0.38	0.11	0.78	0.054
5	7.48	363	32	1.22	2.37	0.52	0.21	1.64	0.063
6	8.76	420	32	1.25	3.27	0.62	0.27	2.38	0.068
7	9.71	463	32	1.30	4.04	0.72	0.31	3.01	0.069
8	6.89	336	32	1.25	2.06	0.49	0.18	1.39	0.062
9	5.17	259	32	1.40	1.25	0.40	0.10	0.74	0.054

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